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BELLOWS FAILURE OF ENERGY DOUBLER MAGNET STRING

PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
BY CRYOGENIC CONSULTANTS, INC.
ALLENTOWN, PA.

FOR

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I. INTRODUCTION:

It is postulated that the junction between two adjacent dipole magnets of the energy doubler will be sheared completely through external action of some device. It is further postulated that the magnet system is under steady state operating conditions, but that the magnets are not powered. Single and two-phase helium and nitrogen will all flow from the break into the environment of the tunnel. Vacuum insulation is lost, and a mixture of air, helium, and nitrogen will enter the vacuum space.

Calculations have been made about the rate of venting into the tunnel based on assumptions for the magnet system supplied by Fermilab.

II. ASSUMPTIONS:

1. All bellows (five) connecting two magnets are sheared, and pipes on either side of the break are in open connection with the atmosphere.
2. Four-hundred (400) ft of magnet on either side of the break will be in open connection with the atmosphere.
3. Inventory of the magnets is as follows:
    a. First 100 ft on either side of the break contain:
        1) Eighty (80) liters of single-phase helium at 1.8 atm and 4.5°K.
        2) Five (5) liters of liquid and 20 liters of gas of two-phase helium at 1.2 atm and 4.42°K.
        3) Twenty-five (25) liters of liquid nitrogen at 1.1 atm and 78°K (saturated).
    b. Last 100 ft on either side of the break contain:
        1) Eighty (80) liters of single-phase helium at 1.8 atm and 4.5°K.
        2) Twenty (20) liters of liquid and 5 liters of gas of two-phase helium at 1.2 atm and 4.42°K.

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3) Twenty-five (25) liters of gaseous nitrogen at 1.1 atm and 78°K.

c. Inventory of the 200 ft between Items a) and b) above will be:

1) One-hundred-sixty (160) liters of single-phase liquid helium.

2) Twenty (20) liters of liquid and 30 liters of gas of two-phase helium at 1.2 atm and 4.42°K.

3) Ten (10) liters of liquid and 40 liters of gaseous nitrogen at 1.1 atm and 78°K.

III. SEQUENCE OF EVENTS AFTER BREAK HAS OCCURRED:

A. Flow of Nitrogen and Helium into the Atmosphere Will Start:

Rate of flow for each of the three circuits is different, as follows:

Nitrogen will flow out at a low rate because initial pressure is at 1.1 atm and total volume of the shields (on either side of the break) contains 35 liters of liquid and 65 liters of gas. The gas expands from 1.1 to 1.0 atm, and the volume increase from this expansion is approximately 6.5 liters. Once this volume expansion has taken place, flow will only be maintained by vaporization of remaining liquid in the line. Rate of vaporization of this remaining liquid is a function of net heat input. This is the difference between heat added from the 300°K level and that transmitted through the gas filled vacuum space to the magnets.

Two-phase helium also is at low pressure. The section nearest the break contains a small fraction of liquid. Initial volume expansion from 1.2 to 1.0 atm will increase the total volume of 100 liters to 119.1 liters. The new volume contains approximately 53.5 liters of liquid. Fluid vented into the tunnel contains 5 liters of liquid and 14.1 liters of gas. This is the equivalent of 863 grams of helium.

Single-phase liquid helium volume expands from 1.8 to 1.0 atm. The expansion process (without heat addition) progresses from Condition 1 to 2 of Table I.

TABLE I

Condition:	1	2
Pressure (atm):	1.8	1.0
Spec. Volume (cc/gr):	8.114	10.05
Temperature (°K):	4.5	4.22
Enthalpy (J/gr):	11.20	10.52
Entropy (J/gr °K):	3.646	3.646

The new volume is homogeneous and

$$\frac{10.05 - 8.11}{8.11} \times \frac{320000}{8.11} = 9{,}438.6 \text{ grams of helium}$$

will vent out of the single-phase system when pressure decays from 1.8 to 1 atm.

The rate of venting is a function of pressure drop in the helium flow system of the magnets. Normal flow rate in the single-phase system is of the order of 30 g/sec in each direction. We can exceed this flow rate by a factor 3-5 and utilize the total pressure available. Rate of venting is then of the order of 200 to 400 g/sec from the single-phase system and probably only 100 to 200 g/sec from the two-phase flow system.

The initial rate of venting will be much higher because of pressure decay in the magnets closest to the break. This high rate, however, will be maintained only for a fraction of a second.

B. Heat Input to the Helium of the Single and Two-phase System:

1. Two-phase Helium System:

The two-phase helium system contains a fairly small inventory of liquid and gas. Heat transfer to this inventory is through a thin skin with large surface area. If the gas flowing into the vacuum space between N_2 shield and helium cryostat is mostly air, heat flux will be high due to condensation and freezing of the air. Fortunately, the rate of heat transfer will drop off when moving along the magnets in a direction away from the break. Rate of air flow along the magnets is a function of velocity and flow area at the point of the break and the rate of air removal through condensation along the magnets. Presence of some superinsulation between the N_2 shield and the helium cryostat severely impedes the flow of air.

Consider the following sample calculation (without superinsulation):

At the point of rupture air rushes in at ambient temperature and atmospheric pressure. Consider the first 20 ft of magnet. Assume:

d_h = .25 in.

T_{av} = 200°K

ρ = .1 lb/cft

At Entrance:

Temperature	=	300°K
Flow Area	=	2 sq in.
Velocity	=	30,000 cm/sec
Pressure	=	.5 atm

Estimated pressure drop along 20 ft of magnet is then:

G = 114,000 lb/hr ft^2

d_h = .25 in.

μ = .048

Re = 50,000

f = .0053

$$\frac{\Delta P}{L} = \frac{.0053 \times (31.67)^2}{193 \times .05 \times .25} = 2.2 \text{ psig/ft}$$

It appears that the available pressure in the air flow system is used up in passing along the first magnet. With the assumed velocity of 30,000 cm/sec at the entrance to the first magnet, mass flow rate of air is approximately 200 g/sec. Maximum heat flux from condensation of this mass is then of the order of 90 kW. Most of this heat will be deposited in the first and second magnets since total surface area available for heat transfer is of the order of 24,000 cm^2 per magnet. Flux is then of the order of 1-2 W/cm^2.

Heating of helium in the two-phase system is extremely rapid, and most of the mass of 400 grams of liquid and gaseous helium will be expelled in the first second. As a result, pressure in the two-phase system near the break will build some to expel this mass. Once the two-phase system in the magnets nearest the break has been cleared of helium, condensation of air moves to the next magnet. However, the rate decreases because impedance in the air system increases through warming of the first magnets and increase in length of flow path.

Flow of air also occurs in the space between nitrogen shield and outside walls. This space is filled with superinsulation,and this reduces the hydraulic diameter by a factor 10 and increases impedance to flow by a factor of 10 or more. The mass flow rate of air on the outside of the N_2 shield is therefore almost certainly less than the flow rate into the space between 2 Ø wall and N_2 shield.

The two-phase system of the first and second magnet will clear out rapidly through the broken connection. The vented helium will mix with air rushing in to bore tube and insulating vacuum space. If a fraction of this helium enters the vacuum space between N_2 shield and two-phase helium channel, rate of heat transfer slows down rapidly. In fact, with time, the insulating vacuum space may be primarily helium and, in that case, the mode of heat transfer to the two-phase helium system will be by conduction through helium gas rather than by condensation.

In general, it appears that the two-phase system attempts to vent its inventory over a period of at least 10 seconds at an average rate of 600 g/sec. This rate is high compared to the normal flow rate of some 30 g/sec of cold fluid. Consequently, the pressure in the two-phase system will increase to the point where it relieves into the low pressure helium gas header. This means that at least part of the two-phase inventory will not be vented into the tunnel through the vacuum break.

2. Single-phase Helium System:

The single-phase helium system contains a large inventory and receives heat from two sources. From the outside it receives heat after the two-phase system warms up due to heat input from 1) above. From the inside it receives heat due to air flow into the bore tube and condensation of this air on the wall of the bore tube. Since impedance to flow at the entrance to the bore tube is smaller than that on the outside of the two-phase system, air flow will be at least at a velocity of 30,000 cm/sec over possibly a large flow area at the entrance to the bore tube.

We will again attempt to calculate the flux of air and heat into the bore tube on the basis of:

a) Pure air enters.

b) A high heat flux ejects helium at a high flow rate from the single-phase system.

c) A large fraction of this helium mixes with the air and winds up in the bore tube.

The bore tube has a flow area of approximately 6 sq in. Wall surface area is approximately .7 ft^2 per ft length. Wall thickness of the bore tube is .025 in.

a) Assume sonic velocity of air at the entrance of the bore tube over an area of 3.6 sq in. at P = .5 atm and at ambient temperature. Mass flow rate into half of the system (one direction) is then:

$V = 30{,}000 \times 3.6 \times 6.45 = 696{,}600$ cc/sec

$\rho = .035$ lb/cft $= 5.6 \times 10^{-4}$ g/cc

$M = 390$ g/sec

To condense this much air, remove heat at the rate of 450 x 390 = 175,500 W.

A maximum rate of air condensation on a wall of 60-70°K would be 1 - 2 W/cm. Assume 2 W/cm^2. Surface area required is then 88,000 cm^2 or 95 ft^2. Total length of bore tube participating in the process is then some 140 ft. The heat flux into the dipole is then of the order of 30 kW. This number is relatively small when compared to the heat deposited during a quench. It appears then that the magnet cryostat will be able to stand the pressure rise. It also means that a considerable part of the single-phase fluid will vent into the helium collection header connected to the relief system.

It also means that helium will be ejected from the first magnet at sonic velocity until the inventory of the first and second magnet is exhausted. After that, helium will flow into the break at a reduced flow governed by temperature and impedance of the single-phase system closest to the break.

b) Because of the high rate of flow from the single-phase system, it is likely that some of this helium will mix with the air flowing into the bore tube. Consider the case of an air-helium mixture entering the bore tube.

At time zero, assume a helium flow rate governed by sonic velocity from the broken tubes. The velocity at low temperature is of the order of 100 m/sec. With a flow area of 1 sq in., flow rate is of the order of 6×10^4 cc/sec or 3,000 to 6,000 grams per second. The first magnet contains approximately 20 liters of liquid or 2,500 grams. Because of impedance assume a flow rate of 1,000 g/sec of liquid helium during the first second. The helium mixes with the air flowing in and the mixture cools. If the rate of mixing is infinite, then the enthalpy of a mixture of

390 g of air and 1,000 grams of liquid helium will result in condensation and solidification of the air by the liquid helium. The final temperature will be of the order of 30-40°K. The volume of 1,000 grams of helium at 1.0 atm and 40°K is 822,000 cc or 30 cft. The volume of 400 ft of bore tube to be filled is some 17 cft. This reasoning indicates that the bore tube may be filled with a helium gas of 1 atm and 40°K carrying a couple of 100 grams of solid air.

If the massive initial flow rate of helium enters the bore tube, heat transfer to the bore tube and single-phase helium system is altogether different. There will be very little condensation of air. Consider the following:

Three-hundred-ninety (390) g of air and 1,000 gr of helium in a mixture at 1 atm will provide a partial pressure of the air of .75 psi. Relative volumes of helium and air are determined from thermal equilibrium at the point of liquefaction of air. It turns out that the air has to give up 390 x 230 = 89,700 joules to reach the point of liquefaction and that the helium only warms to approximately 17°K in cooling the air. At 17°K the helium volume is 12 cft. The air has a volume of 3 cft just prior to condensation. It appears that the bore tube will contain close to 100% of helium by volume. Its temperature will not exceed 40°K. Under these conditions, heat transfer to the single-phase helium will be at a relatively low rate, because:

a. Air freezes in the helium gas of the bore tube and not primarily on the bore tube.

b. Helium gas temperature is of the order of 40°K.

c. Helium gas is more or less stagnant, and heat transfer coefficients are relatively small.

The coefficient of heat transfer with conduction through the stainless steel wall will not exceed 50 Btu/hr ft^2 °F (.028 W/cm °K). Rate is then, with ΔT = 25°K and dipole surface area = 20 ft^2, Q = .028 x 25 x 20 x 930 = 13,000 W. Rate of enthalpy increase of the single-phase fluid is then of the order of 5 joules/gram sec. Once the bore tube is filled with helium gas and is at a pressure of 1 atm, heat input will decrease, and the rate of helium venting from the single-phase channel will be mostly governed by rate of at input from the outside vacuum space.

C. Tunnel Atmosphere:

The tunnel contains approximately 65 cft of gas per ft length. Surface area of walls and equipment is approximately 40 ft^2 per ft length. To cool 65 cft of air to the liquefaction point requires removal of 450,000 joules. Four-hundred-fifty (450) grams of helium will supply this refrigeration. At a venting rate of 900 g/sec, we can cool 2 ft of tunnel volume to 80°K and reduce the air volume to approximately 35 cft. The helium volume will be approximately 570 cft.

It appears that the air will be driven from the area of the break and that in 1 sec some 6-10 ft of tunnel in the area of the break is filled with an 80°K helium-air mixture. From this time on, very little air will enter the vacuum system of the magnets. Heat transfer and rate of venting will be governed by conduction through helium gas. This fortunately reduces heat transfer to a level at which no failures of the magnet cryostats is anticipated.

The two-phase helium system is in immediate thermal contact with the gas in the vacuum space. This gas receives heat from the shield. The shield has a relatively high heat capacity. For instance, 50 lb of shield (estimate) in a dipole magnet will yield 2.4 J/gr or a total of 55,000 joules in cooling from 80 to 60°K. This is sufficient to vaporize all of the liquid contained in the magnet structure.

The rate of heat transfer based on gaseous conduction of helium in the vacuum space will be of the order of 1 to 1.5 kW per dipole magnet. This number is based on a heat transfer surface area of 26 ft^2, a temperature difference of 60°K, and an average thermal conductivity of .5 x 10^{-3} W/cm °K. This rate can be sustained for a period long enough to drive the bulk of the helium out of the two-phase magnet system.

The single-phase system will not receive much heat from the gas in the bore tube, as soon as air is excluded from entry. The helium present will cool to some 5-10°K and, from this time on, the single-phase system will only receive heat from the outside through the two-phase system.

Rate of venting into the tunnel is governed by fluid properties and velocities at the exits of the broken pipes. Flow out of the two-phase system will probably be at sonic velocity until the inventory is exhausted. Some of the fluid in the two-phase system will wind up in the low pressure helium collection header. Total inventory in the two-phase system is 6,700 gr on each side of the break. At sonic velocity through the broken pipes we can vent at a rate of approximately 900 g/sec (P = 1 atm; T = 10°K), assuming a total flow area of 5 cm^2.

The two-phase system, therefore, will be venting for a period of 10-15 seconds before significant decay occurs. The single-phase system will also vent during this time, but possibly at a lower rate due to reasonable insulation. Once the two-phase system has been cleared out, flow from the single-phase system will increase. Inventory of the single-phase system was 80,000 grams. This much liquid will provide 4,600 cft of gas at 1 atm and 80°K. This is the equivalent of 71 ft of tunnel length. A considerable amount of time is required to vent all of this helium in the tunnel.

It appears that air will be essentially excluded from the tunnel in the immediate vicinity of the break. However, cold air is much denser than helium. At 80°K densities are .005 and .0006 g/cc for air and helium, respectively. This means that helium will form essentially a pure atmosphere in the top of the tunnel with possibly an air-rich mixture on the floor. If we assume this, the length of tunnel filled with the mixture will be longer and may be of the order of 100 ft after 10-15 seconds.

IV. CONCLUSIONS:

1. A massive break of all five bellows between two dipoles of the energy doubler will reduce the air concentration in the area of the break to a level in which life cannot be supported.

2. The break will generate an extremely low temperature (less than -250°F) in the area of the break. Chill factors will be high, not only because of the absolute value of the temperature, but also because of high heat transfer coefficients.

3. The insulating vacuum space and bore tube will initially receive a couple of pounds of air from inrushing air. However, after the initial burst, sonic velocity helium flow out of four open tubes will generate a pure helium atmosphere in the vacuum space and bore tube.

4. The magnet single and two-phase system will be pressurized to the point where venting into the collection header will occur. The pressures generated will not be high enough to damage the cryostats. The amount of fluid collected in the collection header may be as much as 50% of the total inventory, because many parallel vent systems are operational in parallel with the four open pipes.

5. The tunnel atmosphere in the area of the break may be considered lethal through the combination of low temperature and lack of oxygen.